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THE AERODYNAMIC SHAPE OPTIMIZATION FOR A SMALL HORIZONTAL AXIS WIND TURBINE BLADES AT LOW REYNOLDS NUMBER

MANOJ KUMAR CHAUDHARY& S. PRAKASH

Department of Mechanical Engineering, Sathyabama Institute of Science and Technology, Chennai, Tamil Nadu, India

ABSTRACT

In this research paper, the main focus on small wind turbine blade performance of two mixed airfoil such as SG 6043 and NACA 4412 and different composite materials are compared by using Numerical with software analysis. The aerodynamic geometry and materials of blade are key parameters to determine staring of the wind turbine and performance of the rotors. The best selection of airfoil and material gives better performance of the wind turbine blade design based on the available wind velocity, Reynolds number. The author wants to compare the performance of mixing for airfoils (SG 6043 and NACA 4412) at Low Reynolds number; less than 250,000.

A parametric numerical study and Simulation was conducted, in order to determine the optimum distribution of chord length and twist angle along the 1 m length of the blade at rated wind speed of 8 m/s. A Blade Element Momentum (BEM) theory based on MATLAB program was developed. The numerical simulation is carried out by Matlab and X-Foil software. The lift-drag ratio are compared based on different angles of attack 2º, 4º, 6º, 8º, 10º at wind velocity 8m/s, rated wind velocity for rural areas. The design chord length of the blade is 1 m and width of the wing is 0.311m. The numerical results from Matlab are compared with the results of X-Foil software; by doing this simulation, understand their blade geometry optimization and the performance of two mixing airfoil profiles is compared. Therefore, the best airfoil will be used in small horizontal axis wind turbine in rural areas where the wind velocity is less. The main focus in this research paper is Reynolds number effect, axial induction effect, Tip loss, Drag effects were considered in the aerodynamic shape optimization and maximized Power coefficient by varying the different of blade sections with optimized tip speed ratio (TSR).

***KEYWORDS:** Composite; Reynolds Number; Solidity; X-Foil & Angle of Attack.*

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Original Article

List of Symbol

a= Axial Interference Factor

a’ = Tangential Interference Factor

A= Area, (area swept by turbine blades)

B= Number of blades

C_d= Coefficient of Drag

Cl= Coefficient of Lift

C_p=Coefficient of Power

c= Chord length

r= Radius to annular blade section

α= Angle of Attack

β= Pitch Angle of Blade to Rotor Plane

U= Tangential Force on Rotor

u = Tangential Wind Speed

U_{rel}= Relative Wind Speed

λ = Tip Speed Ratio

1. INTRODUCTION

Wind power, as an alternative to fossil fuels, is abundant, renewable, and extensively circulated, clean, produces no greenhouse gas emissions during operation and uses little land **[1].** The rotor is the heart of a wind turbine. It consists of multiple rotor blades attached to a hub. The blades are critical components of the rotor, and consist of the airfoil cross sections which interact with the wind. Small wind turbines are self-started at lower wind speed. If the efficiency of a wind turbine is increased, then more power can be generated thus decreasing the need for expensive power generation that causes pollution. Ever since the seventh century, people have been utilizing wind to make their lives easier (Satish et al., 2011).

The earliest work on airfoil design began at 1900's where laminar airfoils were the main focus. Due to the development of computer technologies during the past century, flat plat theory was no longer popular for airfoil design; instead, numerical tools are mainly used for airfoil optimization. Hicks et al. **[2]** Liu et al. and Xudong et al. worked on rotor blade chord and twist distributions. BEM analysis and CFD methods were used to determine the effect of design changes **[3; 4].** OzgePolat and Ismail H. Tuncer worked on aerodynamic shape optimization based on Genetic Algorithm and Blade Element Momentum theory. Optimization studies were performed to maximize power production of specific wind speed, rotor speed, and rotor diameter. In this research, XFOIL was used to provide sectional aerodynamic loads **[5].** Pourrajabian et al. worked on the influence of the air density variation with altitude on the performance of a small horizontal axis wind turbine blade **[6].** Sharifi and Nobari optimized pitch angle, along wind turbine blade, based on an aerodynamic code. This aerodynamic code could accurately predict the aerodynamics of horizontal axis wind turbines **[7]** Wind turbine blade profile is the key to transfer wind kinetic energy to rotational mechanical energy. Standalone small wind turbine applications are mostly interested in electrical generation for remote areas. Due to small size and face to low wind velocity, special design dedicated low Reynolds number airfoils are needed. Due to the dependency of airfoil performance at low Reynolds numbers on the location of the laminar separation bubble, the design philosophies of such airfoils are considerably different than those employed at higher Reynolds numbers **[8-10].**

According to the current research scenarios on the aerodynamic design of the small wind blades, the research perspectives cover a wide range, but the majority of design variables focus on the blade chord length and twist angle [**11].** This research paper presents a BEM method for small wind blade aerodynamic shape optimization and reduced cutting in

wind speed, operated at lower Reynolds number. The NACA 4412, SG 6043 and mixed airfoil NACA 4412 & SG 6043 airfoils were investigated. The Reynolds number effect, axial induction effect, Tip loss, Drag effects were considered in the aerodynamic shape optimization and maximum Power coefficient by varying the different of blade sections. In this paper, the suitable design was obtained for fast running wind turbine rotor by using blade element theory and momentum theory to compute the area under the curve power coefficient vs. tip speed ratio (Cp-λ).

2. SELECTION OF COMPOSITE MATERIAL

A composite material consists of two or more materials combined to obtain properties different from those of the individual materials. Reinforcing fibers (to add strength and stiffness) Matrix (holds and protects fibers, and distributes the load)Polymer Matrix Composite (PMC) materials are typically used in wind turbine blades. Wind turbine blades are complex structures whose design involves the two basic aspects of i) Selection of the aerodynamic shape ii) Structural configuration and materials selection. Modern blades -consist of different kinds of materials (typically composite materials in monolithic or sandwich configuration) Parametric analyses show potential for significant structural improvements both for complete and hybrid/selective use of carbon fibres i)30% to 40% reduction in mass ii)20% reduction in tip deflection for complete replacement of glass with carbon in main spar i)50% reduction in root moment ii) 10% reduction in tip deflection for selective replacement of glass with carbon in the outer span of the blade. The Young‘s modulus, E, of the composite in relation to the Stress strain curve of the components of a composite, is shown in Figure 1. As shown in Figure 1, the resulting modulus of the FRP (fiber-reinforced polymer) composite is midway between that of its constituents: the glass fiber is much stiffer than the matrix resin.

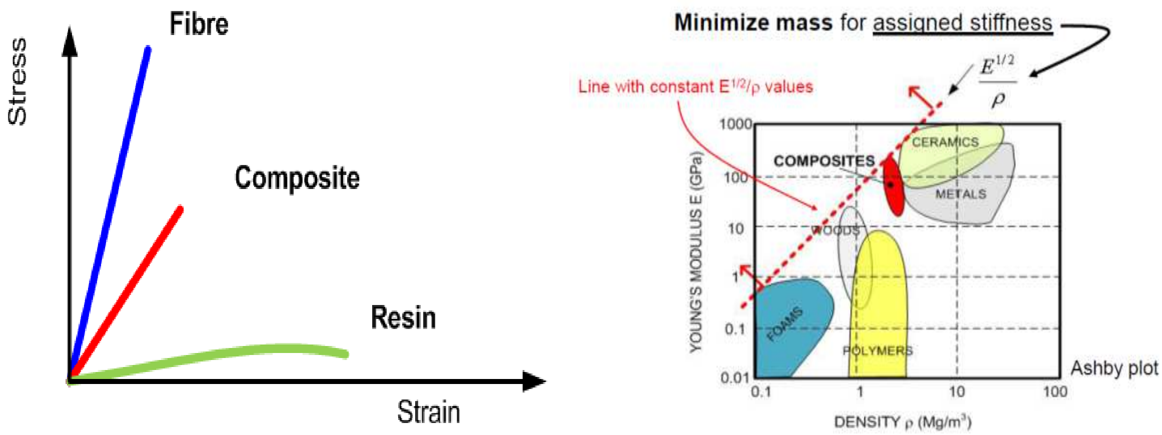

Figure1Demonstrating the Modulus Comparison between Components (Source: SYSWIND Summer School –July 2012 –University of Patras)

3. AERODYNAMIC PRICIPLES & SHAPE OPTIMIZATION

The analysis has been done by using momentum theory and blade element theory. Momentum theory refers to a control volume analysis of the forces at the blade based on the conservation of linear and angular momentum. Blade element theory refers to an analysis of forces at a section of the blade, as a function of blade geometry. The results of these approaches can be combined into what is known as strip theory or blade element momentum (BEM) theory. This theory can be used to relate the blade shape to the rotor’s ability to extract power from the wind. The blade design, analysis covers the following sections, (i) Momentum theory (ii) Blade element theory (iii) Blade-element momentum theory.

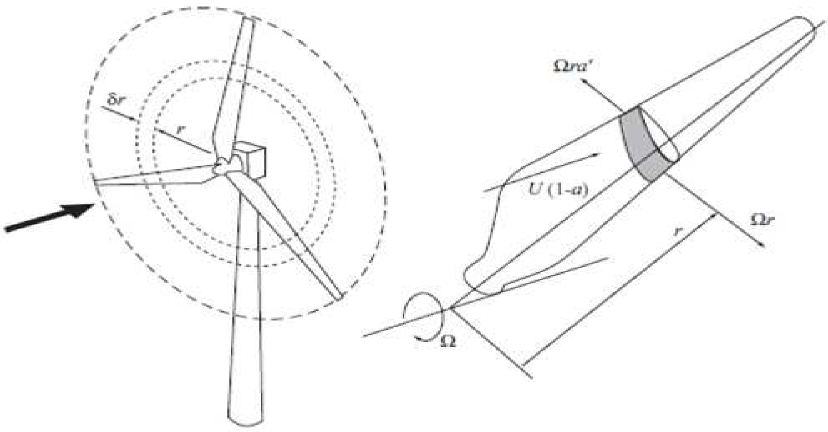

Figure 2: Schematic Representations of Blade Elements (Source: Manwell, 2002). [10]

The differential lift force (dF_l) on an element of a thickness dr of each blade and differential drag force (dF_D) parallel to is given as:

$$dF_l = C_l \frac{1}{2} \rho U_{rel}^{\ 2} cdr \ \& \ dF_D = C_d \frac{1}{2} \rho U_{rel}^{\ 2} cdr \tag{1}$$

The force dF_N normal to the plane of rotation contributes to the thrust and the force dF_T is the torque producing component. These forces act at an angle φ to the plane of rotation.

$$dF_N = dF_L \cos\varphi + dF_D \sin\varphi \ \& \ dF_T = dF_L \sin\varphi - dF_D \cos\varphi \tag{2}$$

The force dF_N normal to the plane of rotation contributes to the thrust and the force dF_T is the torque producing component.

3.1 Design Optimization

The BEM tool calculates the objective function which is the power production of the wind turbine. The Matlab, X-Foil, Airfoil tool supplies aerodynamic data including viscous effects, tip loss, losses due to drag at the blade section from root to tip.

3.1.1Blade Geometry

The blade geometry is another important parameter of the design to be efficient small wind turbine bladegeometry, namely the chord, twist and airfoil type distributions along the span, responds to the output measures of the blade performance. Therefore, the optimal wind blade geometry can improve the overall turbine performance. Blade geometry directly effects on rotor performance and weight of the blade. There is a direct relation between the blade geometry and rotor solidity.

According to the Blade Element Momentum Theory

If the rotor has B blades, the total normal force at a section at a distance, r from the axis is given by: The total tangential force at section at a distance, r from the axis is given by:

$$dF_N = B\frac{1}{2} \rho U_{rel}^{\ 2} (C_l \cos\varphi + C_d \sin\varphi) cdr \ \& \ dF_T = B\frac{1}{2} \rho U_{rel}^{\ 2} (C_l \sin\varphi - C_d \cos\varphi) crdr \tag{3}$$

Thus, from blade element theory, two equations are obtained (Equation 1 and 2) that define the normal force (thrust) and tangential force (torque) on the annular rotor section as a function), Relative flow angle (φ) can also be determined by using following relationship between local tip speed ratio

$$\tan\varphi = \frac{U(1-a)}{\Omega r(1+a')} = \frac{1-a}{(1+a')\lambda_r} \;\&\; \lambda_r = \frac{\Omega r}{U} \tag{4}$$

A number of methods have been suggested for including the effect of the tip loss. The most straightforward approach to use is one developed by Prandtl's (Manwell). This tip loss correction factor characterizes the reduction in the forces at a radius r along the blade that is due to the tip loss at the end of the blade.

$$F = (2/\pi)\cos^{-1}\left[\exp(-\{\frac{(B/2)[1-(r/R)]}{(r/R)\sin\varphi}\}\right] \tag{5}$$

By equating the thrust dT (equations 10) from momentum theory and total normal force dF_N (equation2) from blade element theory, Torque dQ (equations 11) from momentum theory and total tangential force dF_T (equation 2) from blade element theory are Equated the following useful can be expressed as

$$\frac{a}{1-a} = \frac{\sigma' C_n}{4F\sin^2\varphi} \;\&\; \frac{a}{1+a'} = \frac{\sigma' C_t}{4F\sin\varphi\cos\varphi} \quad \sigma' = \text{Local solidity} \tag{6}$$

From Equation (4) to equation (6), Chord length, (c) can be expressed as

$$\text{Chord length, } \boldsymbol{c} = \frac{8\pi raF\sin\varphi\cos\varphi}{(1+a')B\times(C_l\sin\varphi - C_d\cos\varphi)} \tag{7}$$

Where F=tip loss factor; B=blade number; a =axial induction factor; a'=rotational induction factor; C_t = Torque coefficient.

Wind turbine blades use airfoils to develop mechanical power. The cross-section of the wind turbine blades has the shape of airfoils. In the next section 3.2, selection of airfoil with airfoil terminology and airfoil behaviour has been discussed.

3.2Effect of Reynolds Number and Airfoil Optimization Method

The efficiency of the rotor largely depends on the blades profile, in increasing the lift to generate sufficient torque. The airfoil is the one of the fundamental parts of the rotor blade design. Its purpose is to induce suction on the upper surface of the blade to generate lift. Drag is also generated perpendicular to the lift and its presence is highly undesirable. In order to maximize the power coefficient and torque generated, the lift coefficient, (C_L) and the drag ratio (L/D) ratio must be maximized. Higher L/D ratio contribute to higher value of torque and it is desirable that favourable L/D ratio, there is a maximum $C_L$in order to have a small sized rotor.

Small wind turbines experience much lower Reynolds number flow than the large ones, for wind turbine blade design and analysis, it is essential to have the aerodynamic data of the selected airfoil at the corresponding flow conditions, i.e. Reynolds (R_e) numbers. The Reynolds number is defined as:

$$R_e = \frac{\rho V l}{\mu} \tag{8}$$

A rotor radius of 1 m and rated wind velocity 8 m/s, 3 bladed and 6 bladed of a 750 watt wind turbine blade are in table 1.

Table 1: Aerodynamic Parameters Investigated of a 750 Watt Wind Turbine Blade

S.N.	Rotor Radius	No. of Blade	Tip Speed Ratio	Reynolds Number	Angle of Attack	Airfoil Type
1	1 m	3 & 6	4 to 10	5×10^4 to 2.5×10^5	2^o to 12^o	NACA 4412 & SG 6043

As shown in table 1, The Reynolds number is from 5×10^4 to 2.5×10^5 at the angle of attack between 2^o to 12^o. Due to variation of Reynolds number at different tip speed ratio, different angle of attack, the power coefficient, lift coefficient and Lift-drag ratio with the same rated wind velocity 8 m/s. The Reynolds number and tip speed ratio, range and optimized angle of attack, the corresponding lift coefficient and lift-drag ratio were obtained, with this results Airfoils can be customized in wind application for installation of wind turbine in rural areas.

The methodology of blade design Airfoil investigated configuration was given in Table 2

Table 2: Selection of Airfoil Configuration for 1 m Radius of the Rotors

S.N.	Case Type	Airfoil Type	Airfoil Detail	Blade Length
1	I	NACA 4412	Root to Tip	(0.04 m to 1 m)
2	II	SG 6043	Root to Tip	(0.04 mto 1 m)
3	III	Mixed Airfoil	SG 6043 & NACA 4412	0.04 m to 0.5 m, 0.5 m to 1m
4	IV	Mixed Airfoil	SG 6043, NACA 4412 &SG 6043	0.04 m to 0.35 m, 0.35m to 0.7m & 0.7 m to 1 m

As shown in table 1 and table 2 represents all the numerical data used for model validation. The experimental output power was Power coefficient and Lift-drag ratio whereas the numerical output was Electrical power. Airfoils for horizontal axis wind turbines (HAWT) are designed to be used at low angle of attack, where the lift coefficient is high and drag coefficient are fairly low. Airfoil behaviour in the air flow is divided into three phases: the attached flow phase, the high lift/stall development phase and the flat plate/fully stalled phase (Manwell, 2002)**[10].**

3.3 Creating Airfoil

In the run-up to creating a rotor, all its airfoils and the corresponding polar data need to be defined. Airfoils can be created using splines, a SG 6043 airfoil generator or via an import function in XFLR5. Figure 1 indicates that NACA 4412 and SG 6043 airfoil created in X-foil software**. [11]**

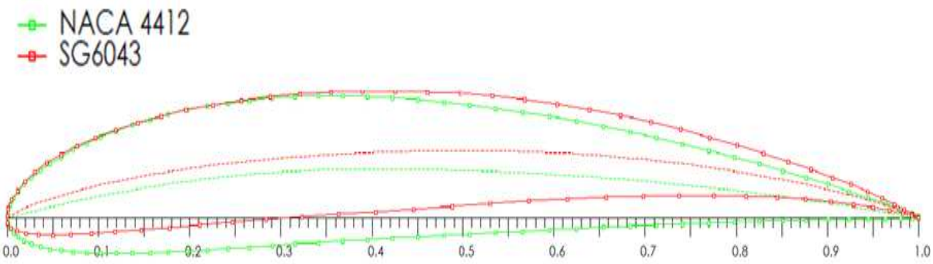

Figure 3: NACA 4412 & SG 6043 Airfoil

3.4 Lift and Drag Coefficient Analysis

In the XFOIL Direct Analysis module, the flow around the airfoils is simulated to create a polar. An analysis can be defined under the menu point Polar, and then the simulation can be started. The analysis will only converge for a limited range of angle of attack values,

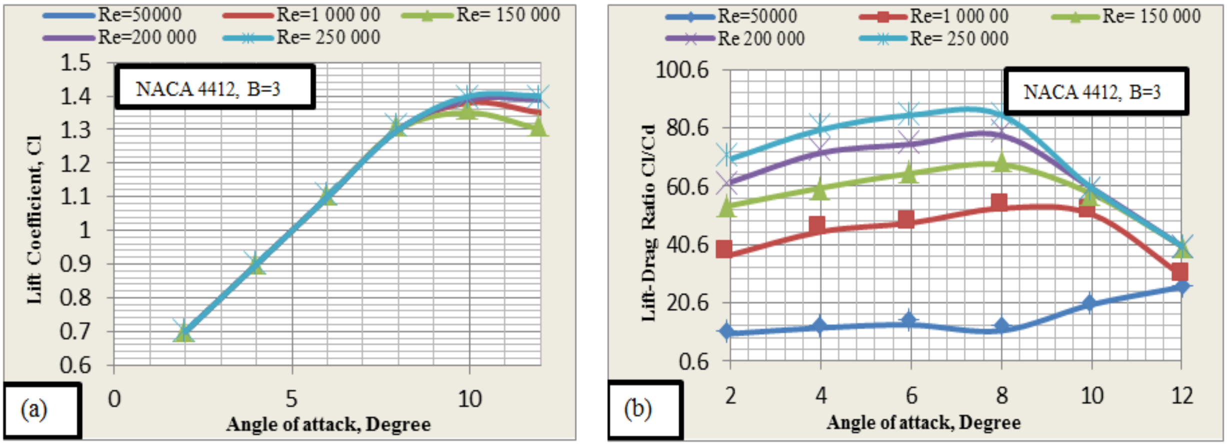

Figure 4(a): Lift Coefficient vs. Angle of Attack (b): Lift-Drag Ratio vs. Angle of Attack for NACA 4412

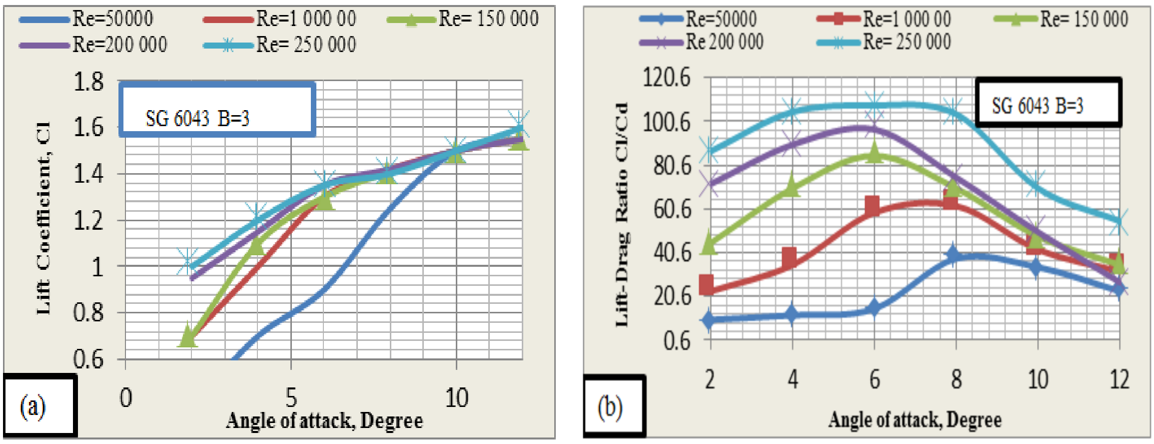

Figure 5 (a): Lift Coefficient vs. Angle of Attack (b): Lift-Drag Ratio vs. Angle of Attack for SG 6043 Airfoil

Figures 4-5shows that maximum lift coefficient obtained at an angle of attack between 7^o to $10^o$for NACA 4412 and SG 6043 Airfoil. It is seen that maximum lift-drag ratio increases rapidly with angle of attack up to which optimum value after which it decreases gradually. The optimum range of the angle of attack is observed lie between 4^o to 6^o at any values of Re.

4. RESULTS AND DISCUSSIONS

For a Specified Angle of attack, the main parameters for wind turbine blade on the aerodynamic shape optimization and number of rotating blades, types of airfoil sections.

4.1 Chord and Twist Angle Distribution along Radial Position of Blade Span

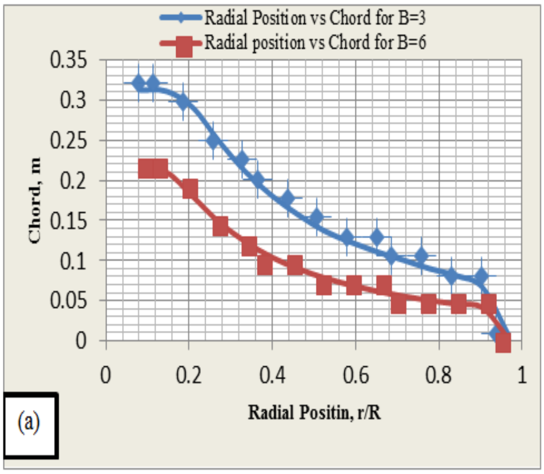

Figure 6(a): Chord Length vs. Radial Position for 3 Bladed & 6 Bladed

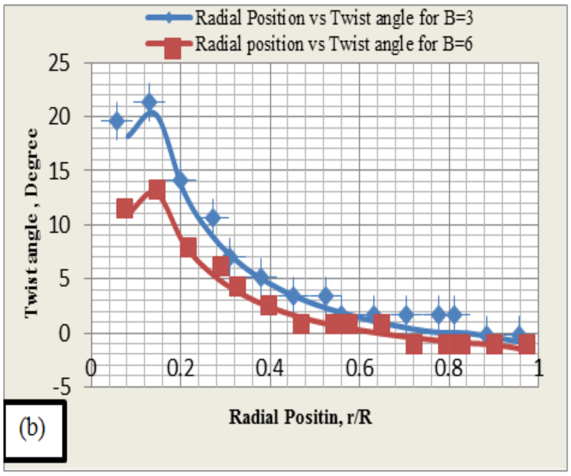

Figure 6(b): Twist Angle vs. Radial Position for 3 & 6 Bladed

4.2 Axial Induction Factor and Solidity along Blade Span

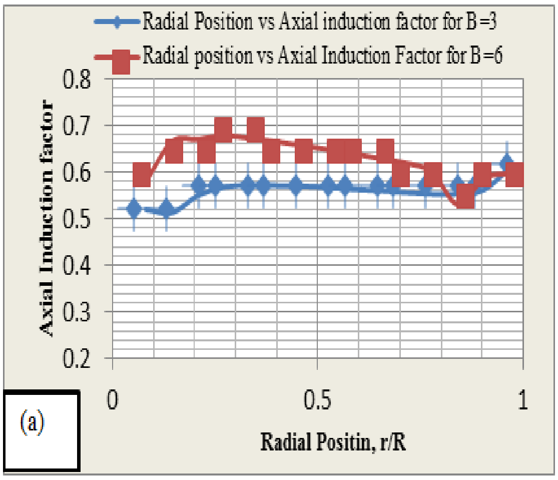

Figure 7(a): Axial Induction Factor vs. Radial Position

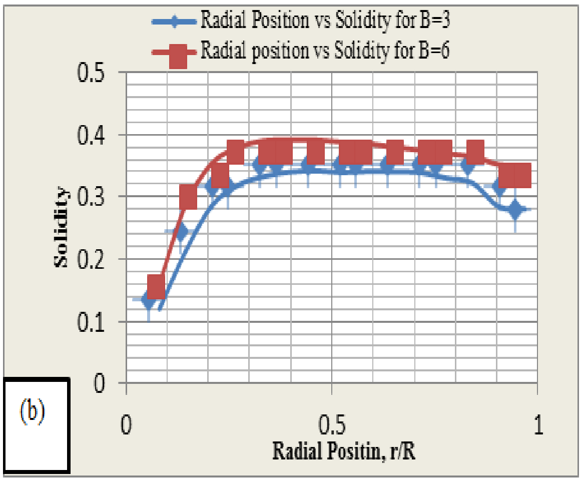

Figure 7 (b): Solidity vs. Radial Position for 3 & 6 Bladed

Figure 6(a) and Figure 6 (b) shows that optimum chord and twist at any radial position for 3 bladed and 6 bladed. It is observed that maximum chord width at root and minimum chord width at tip. However twist angle decreases when increase the radial position of the blade. Figure 7(a) indicates that axial induction factor for 6 bladed should be higher three bladed. Figure 7(b) shows that solidity increases upto blade length 0.3 m after that solidity remains constant up to the tip of the blade.

4.3 Power Coefficients and Output Power

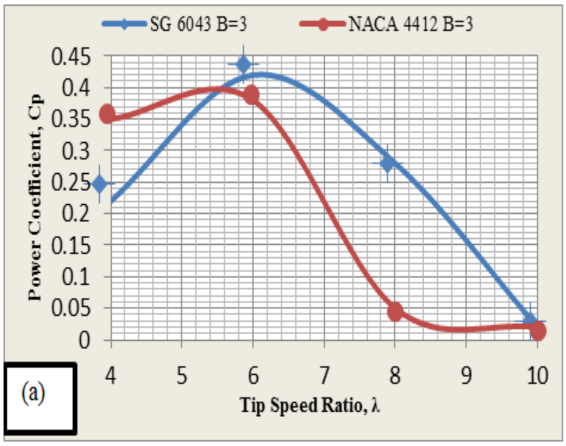

Figure 8(a): Power Coefficient vs. Tip Speed Ratio

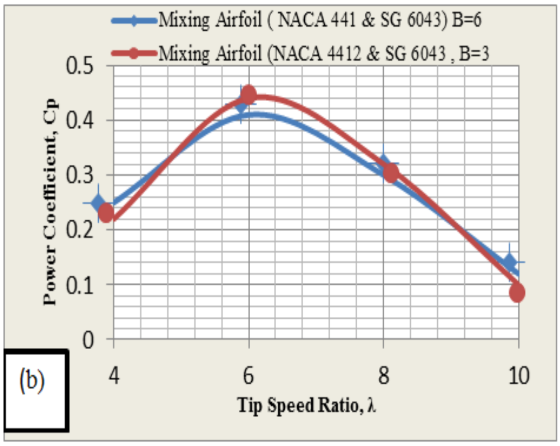

Figure 8 (b): Power Coefficient vs. Tip Speed Ratio for Mixed Airfoil

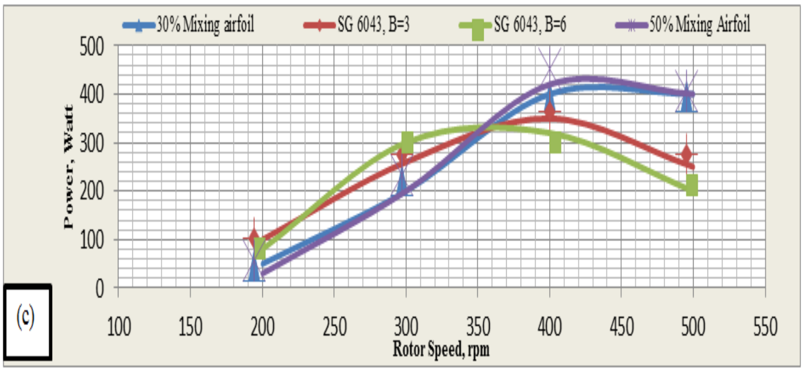

Figure 8(c): Power Vs Angular Velocity

Figure8 (a) and Figure 8(b) Cp-λ performance for SG 6043, NACA 4412 and mixed airfoil, the first point to notice is that maximum value of Cp is only 0.45, for mixed airfoil, achieved at a tip speed ratio of 6, however mixed airfoil performance is better than the SG 6043 and NACA 4412 airfoil. It is seen that Cp increases rapidly with TSR number from 4 to 6, after which is decreases gradually. The optimum range of the TSR is observed to lie in between 4 to 6. Figure 8(c) shows that maximum value of Power output achieved at angular speed is 400 rpm. The optimum range of the angular speed (rpm) is observed to lie in between 350 rpm to 450 rpm for NACA 4412. SG 6043 and mixed airfoil for B=3 & B=6.

4.4 Optimized Small Wind Turbine Blade Model of 750 Watt

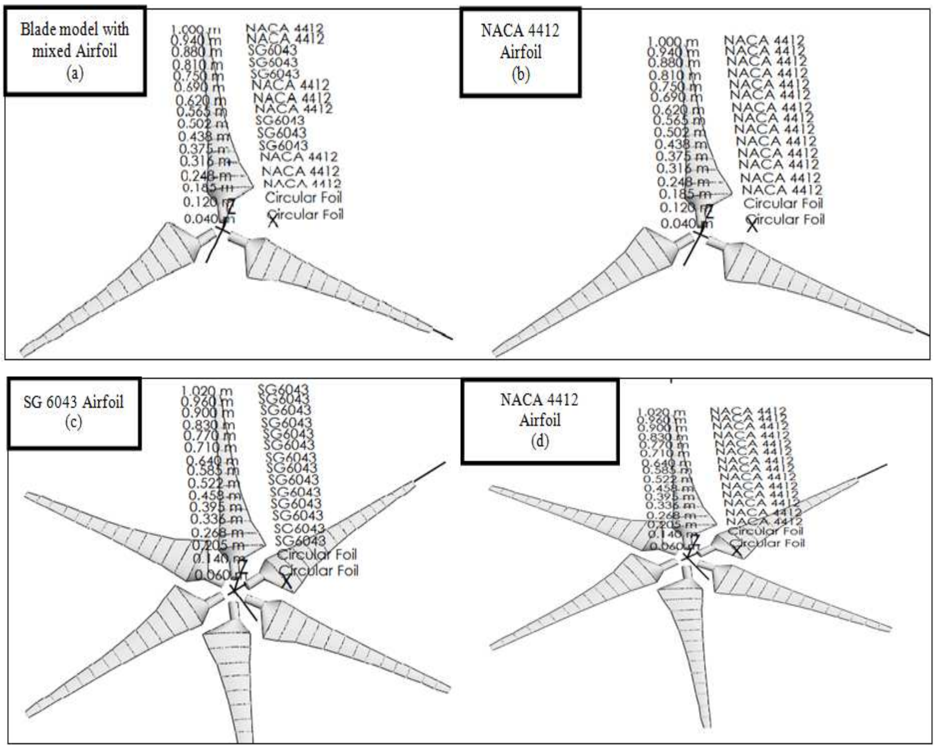

Figure 9(a): Optimized Blade Model mixed airfoil for B=3;
(b): Optimized Blade Model NACA 4412 airfoil for B=3;
(c): Optimized Blade Model SG 6043 airfoil for B=6;
(d): Optimized Blade Model NACA 4412 airfoil for B=6

Figures 9 (a) to 9(d) shows that Aerodynamic shape optimized Blade Model mixed airfoil for number of blade equal to 3, Optimized Blade Model NACA 4412 airfoil for B=3, Optimized Blade Model SG 6043 airfoil for B=6, Optimized Blade Model NACA 4412 airfoil for B=6 at Re number 100 000 and Tip speed ratio equal to 6 with optimized angle of attack is 5^{o}.

5. CONCLUSIONS

In this research paper, we considered the design of a 3 bladed, 6 bladed upwind 750 watt small wind turbine blade with a diameter of 2 m. operated at a rated wind velocity8 m/s and operated rotor rotation speed 200 rpm to 500 rpm. The cut wind speed was 3.2 m/s and cut out speed was 20 m/s. The objectives of this research paperwhere the design of the purpose of best mixed & unmixed airfoil. In this research paper indicated that carbon fiber is the best material for small wind turbine blade. In this research paper indicated that the optimal value of the axial induction factor determined by Betz (a=1/3) is not achievable for real wind turbine blade even in the absence of aerodynamic losses. The results indicated that Case IV configuration of blade profile is the best as compared to the case I, case II, & Case III. It is observed that the maximum power coefficient obtained at the tip speed ratio in between 4 to 6. It is noticed that the maximum value of power coefficient is only 0.44 for mixed airfoil(case IV), achieved at a tip speed ratio of 5 to 6. It is observed that value of power coefficient, lift coefficient& lift-drag ratio obtained at angle of attack in between 4 degree to 6 degrees. It is observed that the approximate 7% to 8 % maximum power coefficient was obtained mixed airfoil for blade number is equal to 3 as compared to blade number is equal to 6. Hence optimum blade number is 3 and material is carbon fiber. Also we conclude that the optimum value of angle of attack is 5 degree and Tip speed ratio is 6 at operated Reynolds

number equal to 100 000. The optimum wind turbine blade reaches 45 % of power coefficient. Moreover it can retain from efficiency of wind velocity of 5 m/s to 8 m/s.

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